AD-774 472

RESEARCH DIRECTED TOWARD THE USE OF LONG AND INTERMEDIATE PERIOD SEISMIC WAVES FOR THE IDENTIFICATION OF SEISMIC SOURCES

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Prepared for:

Advanced Research Projects Agency
Air Force Cambridge Research Laboratories

October 1973

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AFCRL-TR-73-0662

AD774472

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LONG AND INTERMEDIATE PERIOD SEISMIC WAVES

FOR THE IDENTIFICATION OF SEISMIC SOURCES

by

Keith McCamy

Lamont-Doherty Geological Observatory
of Columbia University
Palisades, New York 10964

CONTRACT NO. F19628-71-C-0245

Project No. 1795
Task No. 179500
Work Unit No. 17950001

SEMI-ANNUAL TECHNICAL REPORT NO. 4

October 1973

CONTRACT MONITOR: Carlton E. Molineux
Terrestrial Sciences Laboratory

Sponsored by
Defense Advanced Research Projects Agency
ARPA Order No. 1795
Monitored by
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS, 01730

ARPA Order No. 1795

Program Code No. 1F10

Name of Contractor: Columbia University

Effective Date of Contract:

Contract Expiration Date:

Contract No. F19628-71-C-0245

Principal Investigators and Phone No. Dr. Lynn R. Sykes 914-359-2900

AFCRL Project Scientist and Phone No. Carlton E. Molineux 617-861-3665

1 September 1971

30 September 1974

Qualified requesters may obtain additional copies from the Defense Documentation Center. All others should apply to the National Technical Information Service.

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
Lamont-Doherty Geological Observatory
Columbia University
Palisades, New York 10964

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
RESEARCH DIRECTED TOWARD THE USE OF LONG AND INTERMEDIATE PERIOD SEISMIC WAVES FOR THE IDENTIFICATION OF SEISMIC SOURCES.

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Scientific Interim

5. AUTHOR(S) (First name, middle initial, last name)
Keith McCamy

6. REPORT DATE
October 1973

7a. TOTAL NO. OF PAGES
10

7b. NO. OF REFS
11

8a. CONTRACT OR GRANT NO. ARPA Order No. 1795
F19628-71-C-0245

b. PROJECT NO
1795-00-01

c. DOD ELEMENT
62710D

d. DOD SUBELEMENT n/a

9a. ORIGINATOR'S REPORT NUMBER(S)
SEMI ANNUAL TECHNICAL REPORT NO. 4

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
AFCRL-TR-73-0662

10. DISTRIBUTION STATEMENT

A- Approved for public release; distribution unlimited

11. SUPPLEMENTARY NOTES
This research was supported by the Defense Advanced Research Project Agency

12. SPONSORING MILITARY ACTIVITY
Air Force Cambridge Research Laboratories (LW)
L.G. Hanscom Field
Bedford, Massachusettes 01730

13. ABSTRACT

Seismological research supported by Air Force Contract F19628-71-C-0245 at the Lamont-Doherty Geological Observatory is summarized for the period 1 January to 30 June 1973.

During this period, significant advances have been made in our understanding of the physical processes of natural seismic sources. Intra-plate earthquakes -- the isolated events which occur in the relatively seismically inactive interiors of lithospheric plates -- have been found to display a pattern whose consistency on a global scale is emerging. This pattern provides important constraints on the mechanisms possible for driving plate tectonics as well as reducing the chances of intra-plate earthquakes being misidentified as explosive sources. The intra-plate earthquake swarm at Blue Mt. Lake, N.Y. provided evidence that helped evoke the dilatancy model of the physical process of rock failure, opening the door to the studies of earthquake sources using strong-motion records complement theoretical investigations modelling the dynamics and kinematics of shear failure.

The effects of lateral inhomogeneities on the propagation of surface waves have been dealt with both theoretically by computer modelling and observationally by observing the passage of Love waves across a continental margin.

DD FORM 1 NOV 65 1473 (PAGE 1)
S/N 0102-014-6600

Unclassified
Security Classification

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
intra-plate earthquakes lithospheric plates strong motion Love waves plate tectonics in-situ stress subduction zones thrust faulting overcoring hydrofracture asthenosphere mantle plumes radon emission accelerographs						

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(PAGE 2)

Security Classification

MAJOR SCIENTIFIC ACCOMPLISHMENTS

In the following paragraphs, scientific accomplishments for December thru June 1973, are summarized following the itemization in the statement of work of this contract.

Line - Item 1a

Operation of the Lamont-Doherty network of three long-period and intermediate-period seismographic stations (the Palisades, Sterling Forest, and Ogdensburg) has continued during the last six months.

Line - Item 1b

Intra-plate earthquakes, are fairly common in North America and in Asia. It is these lone type of events within areas that are not normally thought of as highly seismically active that must be identified as earthquakes and not become a false alarm by misidentification as a possible underground nuclear explosion. Many of these events appear to be enriched in the high-frequency part of the spectrum. A preliminary analysis indicates that they fall near the extremity of the earthquake population on an $M_s - m_b$ population and that they do not fall in the explosion population.

It appears likely that intra-plate earthquakes and present-day stresses are closely related to the probable driving mechanisms of plate tectonics. In addition to being of paramount importance to geology, understanding such mechanisms will also permit global generalizations on the nature of intra-plate earthquakes. Sykes and Sbar have studied the focal mechanisms of 79 intra-plate earthquakes as well as other information on in situ stress. Their principle result is that a large percentage of the shocks, particularly those not located near mid-ocean ridges or behind subduction zones,are characterized by a predominance of thrust faulting. In the few areas of the world for which they are available, other determinations of the state of stress from overcoring, hydrofracturing, and recent crustal movements support their conclusion that large areas in the interiors of many lithospheric plates are characterized by high horizontal compressive stresses that appear to be uniform in orientation over sizable regions for the few cases where sufficiently dense data are available. Assuming that the global pattern of stress in the plate interiors has a tectonic origin, these results help to discriminate between proposed mechanisms for driving the plates. For example, high horizontal compressive stress is inconsistent with gravitational sinking as the dominant motive force for the plates. Many of Sykes and Sbar's observations are compatible with plates being driven from below by flow in the asthenosphere or by gravitational sliding or pushing from the general area of ridge crests. There are, however, several focal mechanisms that do not fit the simplest models of gravitational sliding

as the primary motive force of plate tectonics. Finally, the spatial distribution of the directions of principle horizontal stress shows no clear relation to the distribution of hot spots which argues against mantle plumes as a proposed major driving mechanism. Thus their study favors flow in the asthenosphere as the most likely major driving mechanism of plate tectonics.

Work currently in progress includes developing a tectonic framework for the observed seismicity in central Asia. Both spatial and temporal distribution of seismicity, as well as fault plane solutions, are being employed toward the evolution of a large scale tectonic model. Previous work on this subject has been limited to larger events, generally to events of m_b greater than 5.5. Recently, techniques have been developed [Tatham and Savino, 1973] for using Very Long Period Seismograph Stations to discriminate between possible focal mechanisms by observation of long-period surface waves. This technique has been applied to events of m_b less than 4.0 at distances of about 8° and has been expanded to use the long-period components of WWNSS Stations. The method is presently being modified for use in central Asia. The modification involves using known fault plane solutions to smaller events in adjoining regions. This method offers the potential for greatly expanding data available for developing a tectonic model of the region, as well as offering a possible tool for discrimination between observed anomalous events and underground nuclear explosions.

Line - Item 1c

1. Rupture zones and possible locations of large earthquakes along the western and northern boundary of the Phillipine Sea plate.

Large, shallow earthquakes ($M > 6.9$) that have occurred since 1968 have been relocated to determine whenever possible the extent of rupture along the northern and western boundary of the Phillipine Sea plate. Two areas along the seismic zone east of Mindinao have not experienced a large, shallow, earthquake in at least 30 years and are areas of special seismic potential. A compilation of historic, microscopic, and relocated instrumental data shows that the Phillipine fault which runs about 1200 km from Luzone to Mindinao probably has ruptured over at least half its length during the last 105 years. Consequently, the activity at the Phillipine fault indicated that plate motion in this region may be partially or totally accommodated by this fault.

The Ryukyu Island arc, between 123° and 130°N, has not experienced a large shallow earthquake in 50 years and is relatively aseismic for a plate boundary. A study of historic Japanese sources indicates, however, that large, destructive earthquakes with associate tsunamis have occurred along this

portion of the plate boundary is an area of special seismic potential.

Line - Item 3e

Recent work casting much light on the actual physical processes taking place at an earthquake hypocenter has been supported, in part, by this contract. Scholz, Sykes, and Aggarwal have developed the rock dilatancy-water diffusion model of the earthquake source region from a diverse set of data, some of which was obtained from the seismograph network around the Blue Mt. Lake earthquake swarm. This dilatancy model goes far toward explaining the nature of an earthquake source before, during and after failure. They show that precursory effects such as crustal movement, changes in seismic velocities, tilts, fluid pressure, electrical and magnetic fields, radon emission, and frequency and distribution by magnitude of small local shocks occur before many, perhaps all, shallow earthquakes and demonstrate that these heretofore unrelated premonitory effects occur at a characteristic time before the earthquake which is directly relatable to the magnitude of the event. This physical basis promises to lead us soon to quantitative deterministic earthquake prediction.

Briefly, the model describes a sequence of events that occur before failure. As the ambient stress rises in the source region due to tectonic forces the rock undergoes an inelastic increase in volume produced by cracks forming and propagating. This phenomenon is called dilatancy and can occur at stresses as low as half the breaking strength of the rock. While cracks are forming and for some time after, the rock will be undersaturated because of the finite time it takes water to diffuse in to fill the new cracks. The undersaturation of the rocks causes the propagation velocity of P waves to decrease, as well as several other observed premonitory effects. In addition, the undersaturation decreases the pore pressure in the dilatant region and hence increases the effective stress, a phenomenon called dilatancy hardening, which actually strengthens the rock, inhibiting rupture despite a continued rise in ambient stress. As fluid flows into the dilatant region the new cracks fill and the rock becomes more saturated. The pore pressure cannot begin to rise until the rock is wholly saturated but when it does, it lowers the effective stress, weakening the rock. Since the tectonic stress continues to rise during the dilatant period, the rising pore pressure triggers the earthquake just as it does through fluid injection or reservoir filling. Thus dilatancy first delays the earthquake by reducing fluid pressure on the fault, then triggers it when the pore pressure is recovered. The time scale of this sequence of events is controlled by the diffusion of fluid and consequently depends on the size of the dilatant region, relating the duration of the premonitory stages to the magnitude of the earthquake.

This theory, in addition to promising exciting advances in earthquake prediciton, provides the first comprehensive physical description of the nature of the earthquake source region. To date, the dilatancy model seems to apply best to intraplate events where the dominant stress is compressional. Extending the model to other stress regimes is an active area of research.

3. Five accelerograms recorded near the southeast end of the rupture of June 27, 1966 earthquake at Parkfield, California have been doubly integrated to give ground displacement records. Theoretical ground displacements were calculated for comparison based on a smoothly propagating ramp in a homogeneous half space. The theoretical displacement agreed reasonably well with the observations of horizontal motion before the arrival of the surface waves, with a best fitting propagation velocity of 2.8 to 3.0 km/sec. A paper describing this modelling of an earthquake source is in press with the Bulletin of the Seismological Society of America.

Line - Item 1f

1. A combined theoretical and observational study of the refraction of Love waves employs a method developed for calculating reflection and transmission of inhomogeneous SH waves. The components of the Love waves in the appropriate media are determined to obtain the transmission and reflection coefficients for Love waves. This technique agrees excellently with previous finite element results. A typical calculation takes .02 seconds on an IBM 360, Model 91, which compares most favorably with the 10 to 20 minutes required for the equivalent finite element computation. Love-wave transmission and reflection has been numerically investigated in models of a continental margin. The boundary conditions are satisfied exactly at the interface between the oceanic and the continental model. Diffracted waves for the problems investigated can be considered to have a minor influence, since most of the energy is in the transmitted or reflected Love waves.

Preliminary observations of the transmitted Love wave amplitudes have been made at the ocean bottom seismic station, OBS, and the nearby seismic station Byerly, BKS, in Berkeley, California. The transmitted amplitudes are strongly dependent on period. For propagation from the ocean to the continent, the transmitted amplitudes are largest for the shortest of the observed periods, 20 sec. For propagation from the continent to the ocean, the transmitted amplitudes are largest for the longest of the observed period, 60 sec.

To explain the observed trends in the data it is found necessary to use models that have a low-velocity layer in the mantle under the ocean.

A very large change in amplitude at the crossing of the continental margin as well as the transmission dependence on

angle incidence is presently under investigation.

2. Richards has investigated a dynamic model of earthquake faulting to help quantify the stress drop associated with an earthquake. His model nucleates at the fault motion at a point and allows the rupture to spread. When the rupture zone grows over a large part of the fault surface, the particle velocities become proportional to the stress drop. The proportionality constant may vary for a variety of earth material. Westerly granite, for example, gives 60 cm/sec particle velocity for each 100 bars of stress drop. A paper describing this work is in press with the Journal of Applied Physics.

3. A major problem in the development of a theory for seismic body waves lies in the fact that P and S waves do not propagate independently in a heterogeneous medium like the earth. Richards has approached this problem in terms of potentials for P and S waves, and it has been found possible to display a coupling coefficient between P and SV motion. The method permits many known solutions for scalar waves in the heterogeneous media to be adapted to the study of P waves in seismology. A manuscript describing this potential method is nearing completion, with submission to the Bull. Seis. Soc. of Amer. expected before the end of September.

LIST OF PERSONNEL

Scientists:

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K.H. Jacob (N/C)
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P.G. Richards
L.R. Sykes
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Graduate Students:

Y.P. Aggarwal
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Engineers:

W.A. McDonald

Problems Encountered:

None

Fiscal Status:

Estimated expenses through the close of the present contract period: $250,490

Total cost to completion of contract: $278,316

Action Required by the Government:

None

Future Plans:

Future plans call for the continuation of the research outlined above and in other areas specifically related to the VELA-UNIFORM program.

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Anderson, J. A Dislocation Model for the Parkfield Earthquake, in press, Bull. Seis. Soc. Amer.

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Papers Presented at Meetings

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Gregersen, S. and L.E. Alsop, Amplitudes of Horizontally Refracted Love Waves, presented at the Meeting of Seis. Soc. Amer., Colorado School of Mines, Golden, Colo., May 16-19, 1973.

Richards, P.G., Dynamic Properties of an Earthquake Source, Presented at 5th World Conference on Earthquake Engineering, Rome, Italy, June 19, 1973, to be published in preceeding volume.